What Hath RHIC Wrought ? : The Chiral Restoration Phase Transition Found at RHIC

Gerald E. Brown, [a] Chang-Hwan Lee [b] and Mannque Rho [c]

[a] Department of Physics and Astronomy,
State University of New York, Stony Brook, NY 11794, USA
(E-mail: Ellen.Popenoe@sunysb.edu)

[b] Department of Physics, Pusan National University, Pusan 609-735, Korea
(E-mail: clee@pusan.ac.kr)

[c] Service de Physique Théorique, CEA Saclay, 91191 Gif-sur-Yvette cédex, France
& Department of Physics, Hanyang University, Seoul 133-791, Korea
(E-mail: rho@spht.saclay.cea.fr)

Abstract

Given Brown/Rho scaling[1] we thought of the mesons which are observed in Nambu-Jona Lasinio theory as collective modes. The π, σ, ρ and A_1, should go smoothly through T_c as the temperature rose, going massless as T comes to T_c [2,3].

In a general sense, this is what happens; namely it can be seen directly from the increase in entropy above T_c in lattice gauge simulation (LGS) that there are 32 essentially massless excitations just above T_c, the number of degrees of freedom in the mesons denumerated above, together with their isospin partners (There is no dependence on isospin above T_c.) These 32 degrees of freedom are called instanton molecules; equivalently, chirally restored mesons.

The most straightforward way to construct the chiral restoring phase transition is to make the π and σ masses, in the chiral limit, zero on both sides of T_c; i.e., to carry the π and σ mesons smoothly through T_c since the transition, from the point of view of the mesons which dominate RHIC physics, is second order. Here the first surprise was encountered. LGS showed the quark and antiquark masses to be $\gtrsim 1 GeV$ above T_c. That means that to make the π and σ massless, they must be bound by an attractive interaction which is strong enough to provide 2 GeV binding energy.

Lattice calculations showed that the Coulomb (color singlet) interaction increased substantially as T went above T_c. (In response to the chiral symmetry breaking order parameter of $4\pi f_\pi \sim 1$ GeV, this parameter, going to zero and

Preprint submitted to INPC2004 *2 February 2008*

the thermodynamic variables, the meson masses being zero, the gauge coupling jumps back towards the infrared at T_c. Just above T_c the attractive Coulomb interaction plus the Ampere's law velocity-velocity interaction which together give a color singlet gauge coupling of $\alpha_s = 1$, bind the quark and antiquark by ~ 0.5 GeV, 1/4 of the way down to zero from the 2 GeV sum of quark and antiquark thermal masses.

In fitting the temperature dependence of the melting of the soft glue, Brown et al. [4] could fit the curve of the LGS by a four-point Nambu-Jona Lasinio interaction, which has only two parameters, the coupling G which includes all information about gluonic interactions, and the cut off Λ. The surprising result was that G decreased by only 6% in going through chiral restoration at T_c. Thus, one had the strength of the NJL above T_c, little changed from below T_c. (G comes mainly from the 't Hooft interaction which decreases only little at T_c.)

Now the Coulomb bound states, the so called Furry representation, furnished a representation of completely degenerate quark-antiquark bound states. The Nambu-Jona Lasinio connected all of these states, with equal, attractive matrix elements. The problem is just that of Brown's giant dipole collective state except that the π and σ collective modes are those of Goldstone modes, or Anderson modes in a superconductor. They must be of zero mass at T_c if a smooth, essentially second order except for the few baryons, transition is to be made at RHIC, so we are guided by the chiral symmetry.

The way in which these modes are made massless is simple, but instructive. Namely, since the quark and antiquark each have large thermal masses of ~ 1 GeV, they must be brought down to zero mass by very strong attractive interactions, with coupling constants $g_{\rm eff} \sim 7$. Because of this the massless chirally restored mesons are extremely tightly bound, and summing quark-antiquark states to make them into vibrations brings them down in radius to ~ 0.1 fm.

With increasing temperature above T_c, roughly at $1.5T_c$, Debye screening sets in and the Coulomb attraction weakens. Also, as the "epoxy" (hard glue) melts, the NJL four-point interaction weakens and at $T \lesssim 2T_c$ the bound states break up. For temperatures $\gtrsim 2T_c$ the perturbative nature probably sets in, but RHIC does not go more than $\sim 2T_c$.

The early universe went through the phase of $\bar{q}q$-bound states, essentially chirally restored mesons, ~ 10 microseconds following the big bang.

One of the best features of the chirally restored mesons is that they are seen in lattice gauge simulations, as giant resonances[5], very similar to the giant dipole resonance in nuclear physics. We show these results in Fig. 1. They have a complete SU(4) symmetry, as described by the theory, scalar, pseu-

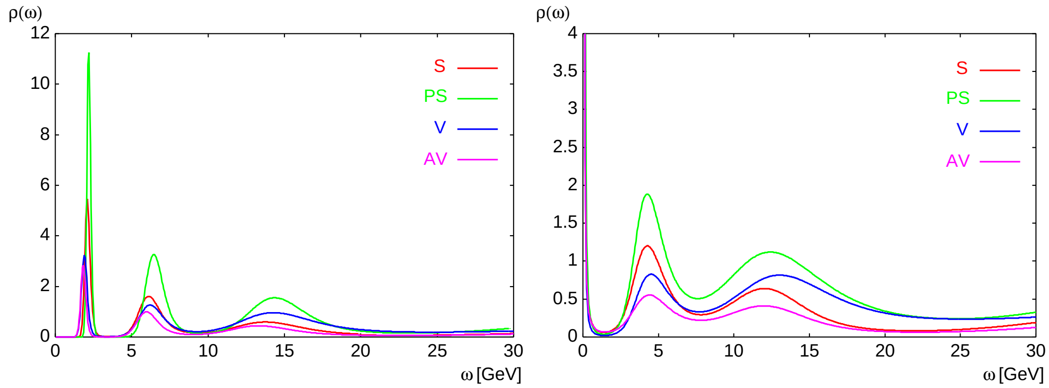

Fig. 1. Spectral functions of Asakawa et al.[5]. Left panel: for $N_\tau = 54$ ($T \simeq 1.4T_c$). Right panel: for $N_\tau = 40$ ($T \simeq 1.9T_c$). In each graph only the lowest vibrations is physical; the higher ones are lattice artifacts. Also these lattice results are only for heavy quarks. With the additional (attractive) interactions noted above the lowest vibration at $T = 1.4T_c$ moves down nearly to zero energy.

doscalar, vector and axial vector excitations being degenerate. There is no isospin dependence. The chirally restored mesons are collective vibrations.

The change in constituent behavior is particularly interesting in going from below T_c to above T_c. As T goes up to T_c from below, the rho meson mass goes to zero in the chiral limit[6], also the $g_V^\star \to 0$. The ρ decouples from the pions. The equation of state of the large number of massless, weakly interacting particles becomes very soft.

In going above T_c the interactions become very strong, strongest just above T_c where the masses of the chirally restored mesons are brought to zero (in the chiral limit). Above T_c, with chiral restoration, the ρ and A_1 are equivalent as are the π and σ.

As noted earlier the interactions show no isospin dependence. Since there are only two different species, π and ρ, nonlinearity in the vibrations has to come from the reaction

$$\rho \leftrightarrows 2\pi. \tag{1}$$

This nonlinearity has been estimated [7], resulting in a width $\Gamma(\rho \to 2\pi)$ estimated as ~ 380 MeV. The region of temperature just above T_c is, therefore, the most strongly interacting region, and chemical equilibration of the various species is assured. As the temperature decreases from above T_c to below T_c in the expansion of the fireball in RHIC, the hot material goes from the strongly interacting region in which it is equilibrated into the very weakly interacting region below T_c. Thus, chemical freezeout comes as the system goes from $T_c+\epsilon$ down to $T_c - \epsilon$, the band of energies which are mixed by the explicit chiral symmetry breaking, $\epsilon \sim 5$ MeV.

The chemical freezeout occurs with the hadrons off-shell. (Just above T_c they are dynamically bound into colorless chirally restored mesons.) Whereas most of the abundances which result from chemical freezeout at $T_c - \epsilon$, with the hadrons considered as on-shell, are the same as if the hadrons are equilibrated off-shell above T_c, the ρ/π abundances are quite different, because the ρ has a low-mass-estimated to be $m_\rho^\star = 2m_\pi$ at $T_c+\epsilon$ so that the ρ/π^- ratio measured by STAR is doubled in our scenario [7]. In fact, at $T_c + \epsilon$ our calculated equilibrium abundance of ρ's is 2-4 times greater than would be found by equilibration on-shell at $T_c - \epsilon$, where it is usually assumed in calculating abundances [8].

We outline above not only what we have done to establish the properties of the chirally restored mesons, but a whole scenario is laid out for the experiments now underway at RHIC. Not only will the equilibrium abundance of the ρ-meson be established better by STAR at $T_c + \epsilon$ (With the present STAR systematic error, the uncertainty is a factor of ~ 2.), but the dileptons from the decay of the chirally restored ρ should be seen. Unfortunately, most of them will come in a wide swath with invariant mass from 0 to 400 MeV, just where the “cocktail” background is largest. However, the large number should add appreciably to the background, and the excess from the usual hadronic ρ coming in the mixed phase should be significantly increased around 400 MeV.

Acknowledgments

G.E.B. was supported in part by the US Department of Energy under Grant No. DE-FG02-88ER40388. C.H.L. was supported by Korea Research Foundation Grant (KRF-2002-070-C00027) and Pusan National University Research Grant.

References

[1] G.E. Brown and M. Rho, Phys. Rev. Lett. **66** (1991) 720.

[2] G.E. Brown, H.A. Bethe and P.M. Pizzochero, Phys. Lett. **B263** (1991) 337.

[3] G.E. Brown, A.D. Jackson, H.A. Bethe and P.M. Pizzochero, Nucl. Phys. **A560** (1993) 1035.

[4] G.E. Brown, L. Grandchamp, C.-H. Lee and M. Rho, Physics Reports, 391 (2004) 353.

[5] M. Asakawa, T. Hatsuda and Y. Nakahara, Nucl. Phys. **A715** (2003) 863c.

[6] M. Harada and K. Yamawaki, Phys. Rep. **381** (2003) 1.

[7] G.E. Brown, C.-H. Lee, and M. Rho, hep-ph/0405114, Nucl. Phys. A, submitted.

[8] P.G. Braun-Munzinger, K. Redlich, and J. Stachel, Invited Review for "Quark Gluon Plasma 3", eds. R.C. Hwa and Xin-Nian Wang, World Scientific; nucl-th/0304013.